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Sanduleanu et al.

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(54) **SPEED OF LIGHT BASED OSCILLATOR FREQUENCY**

(2013.01); *H03B 5/1215* (2013.01); *H03B 5/1841* (2013.01); *H03B 5/1852* (2013.01); *H03L 7/24* (2013.01)

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(58) **Field of Classification Search**

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USPC ..... 331/96, 107 SL, 154  
See application file for complete search history.

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*H03B 5/18* (2006.01)  
*H03B 1/00* (2006.01)  
*H03L 7/24* (2006.01)  
*H03B 5/12* (2006.01)

(52) **U.S. Cl.**  
CPC ..... *H03B 5/1847* (2013.01); *H03B 1/00*

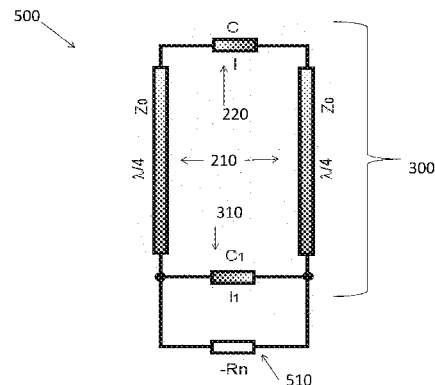
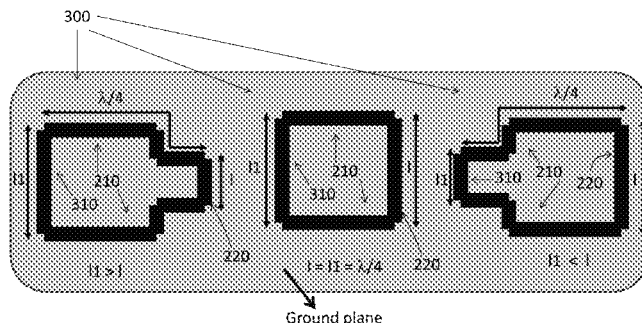
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(57) **ABSTRACT**

An oscillator and a method of fabricating the oscillator are described. The oscillator includes a resonator with a plurality of transmission lines. An oscillation frequency of the oscillator is independent of at least one dimension of the plurality of transmission lines. The oscillator also includes a negative resistance circuit coupled to the resonator that cancels internal loss resistance of the resonator.

**9 Claims, 16 Drawing Sheets**



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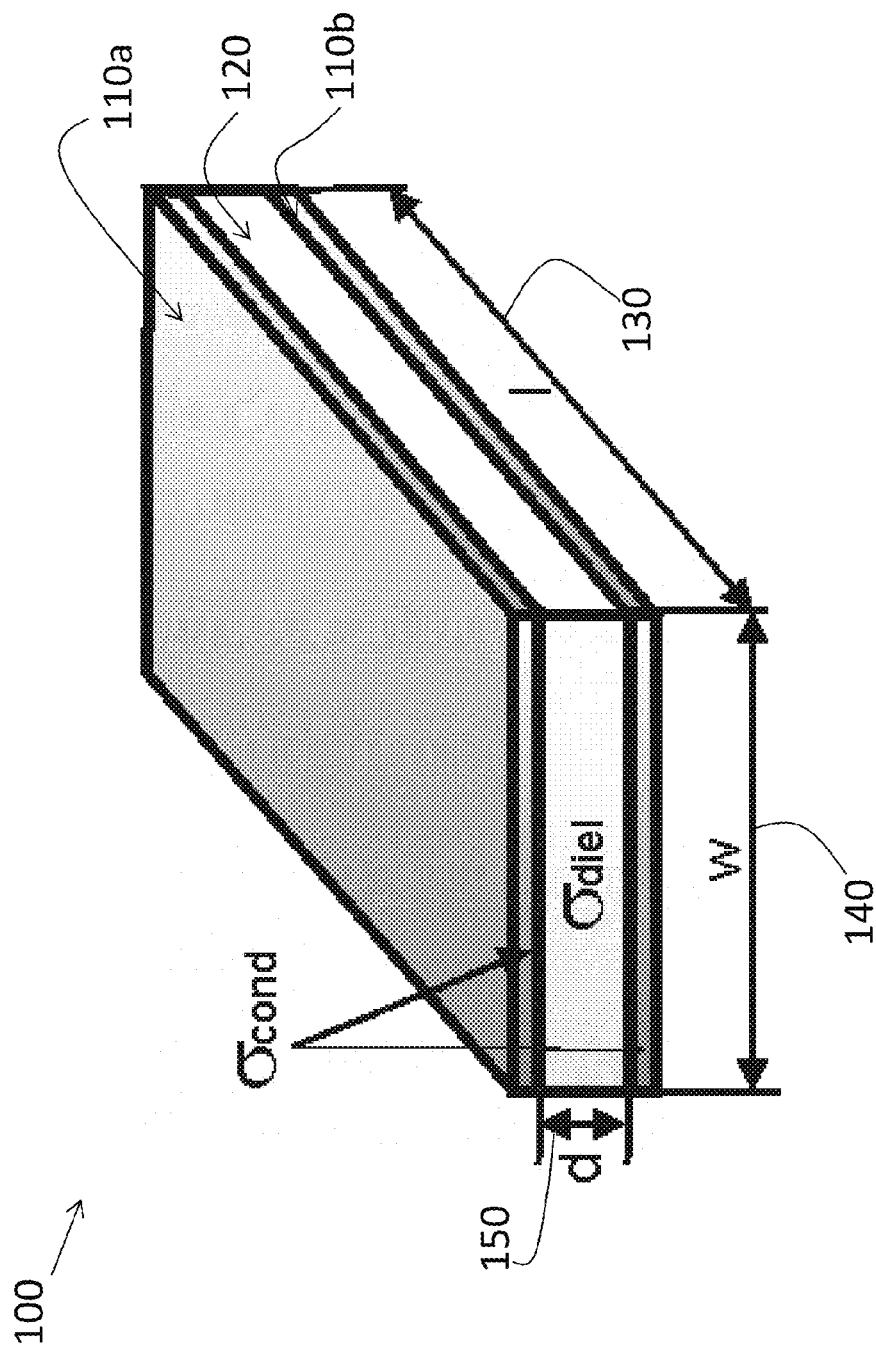


FIG. 1

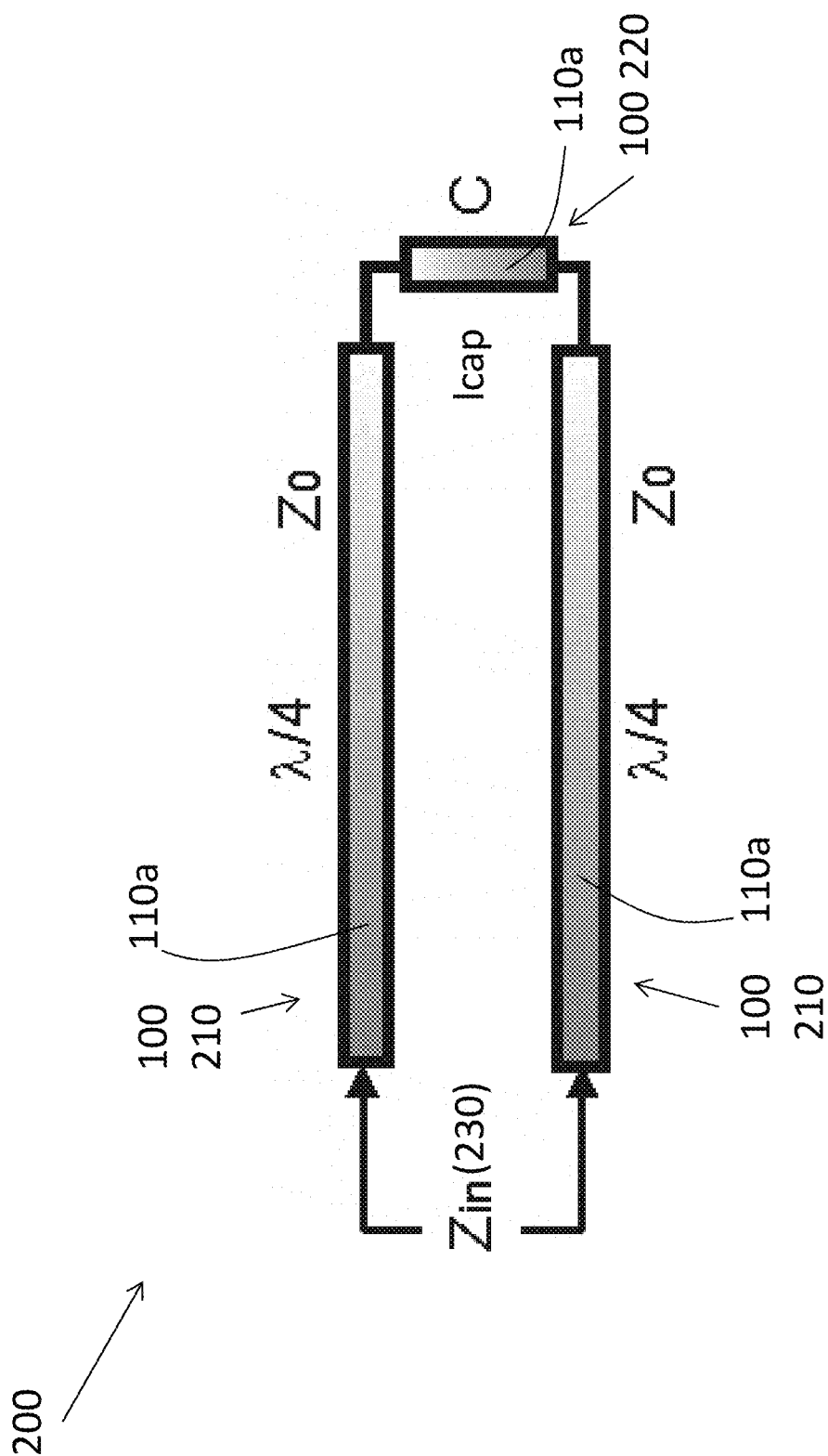


FIG. 2

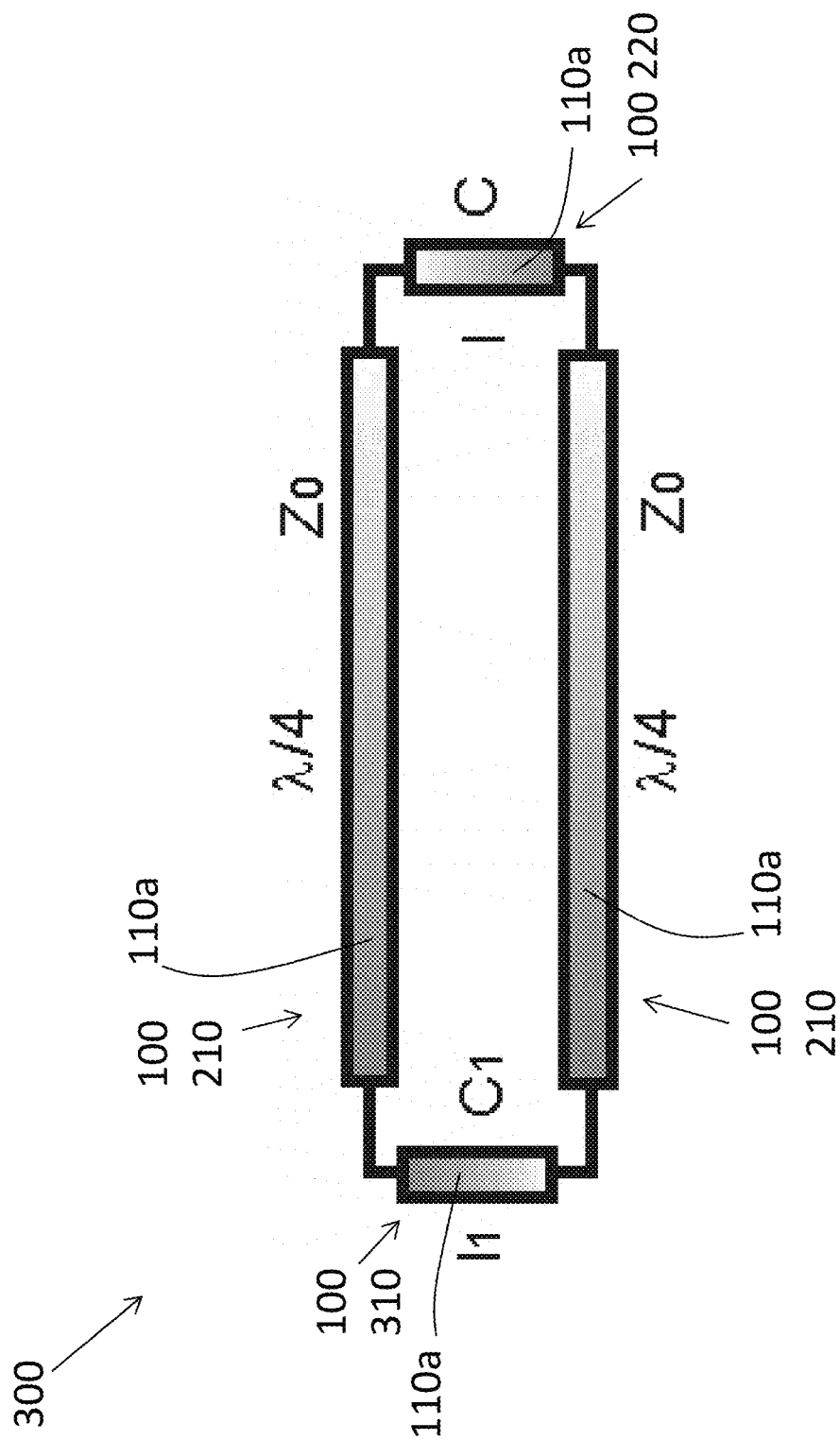


FIG. 3

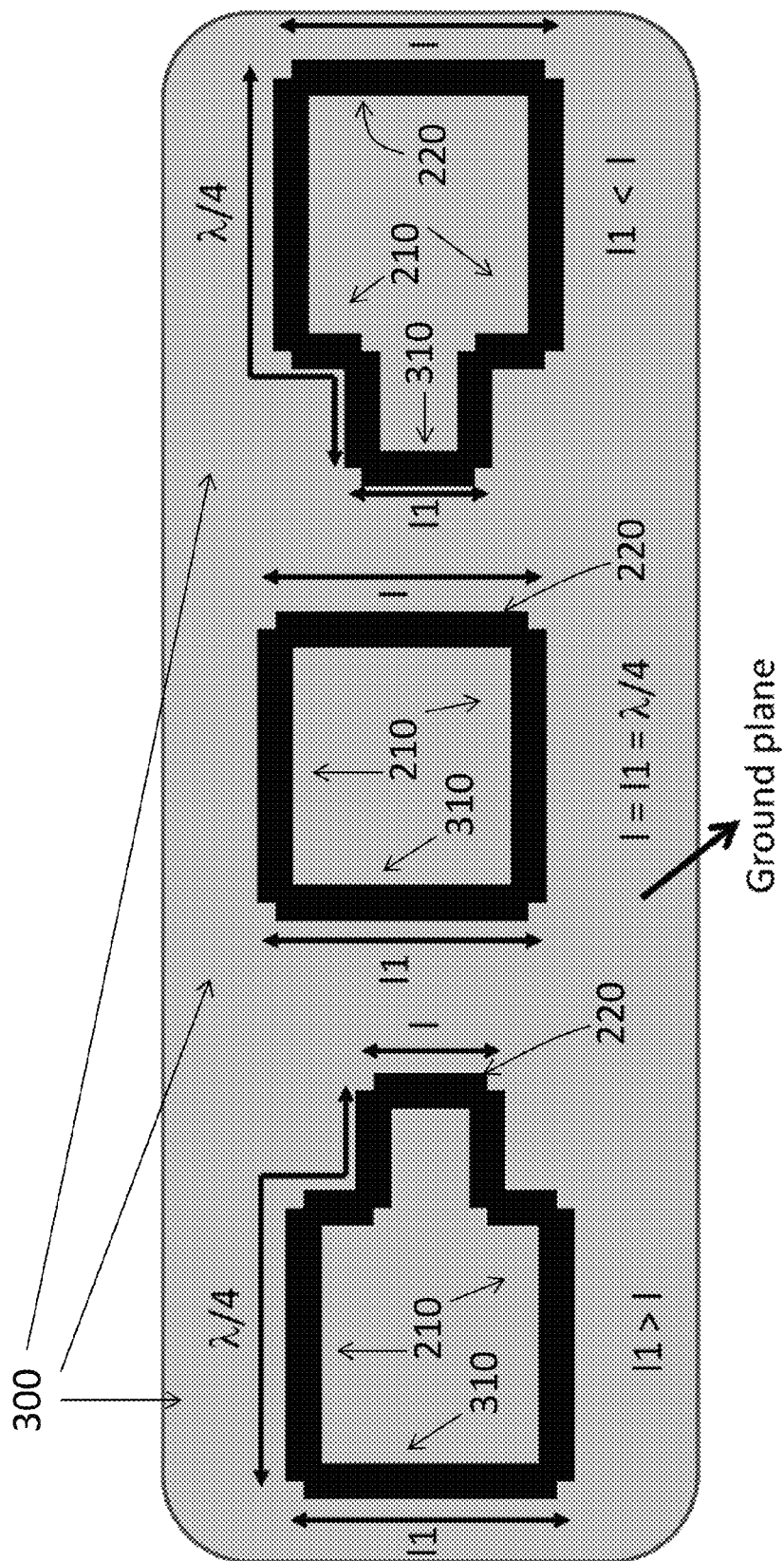


FIG. 4

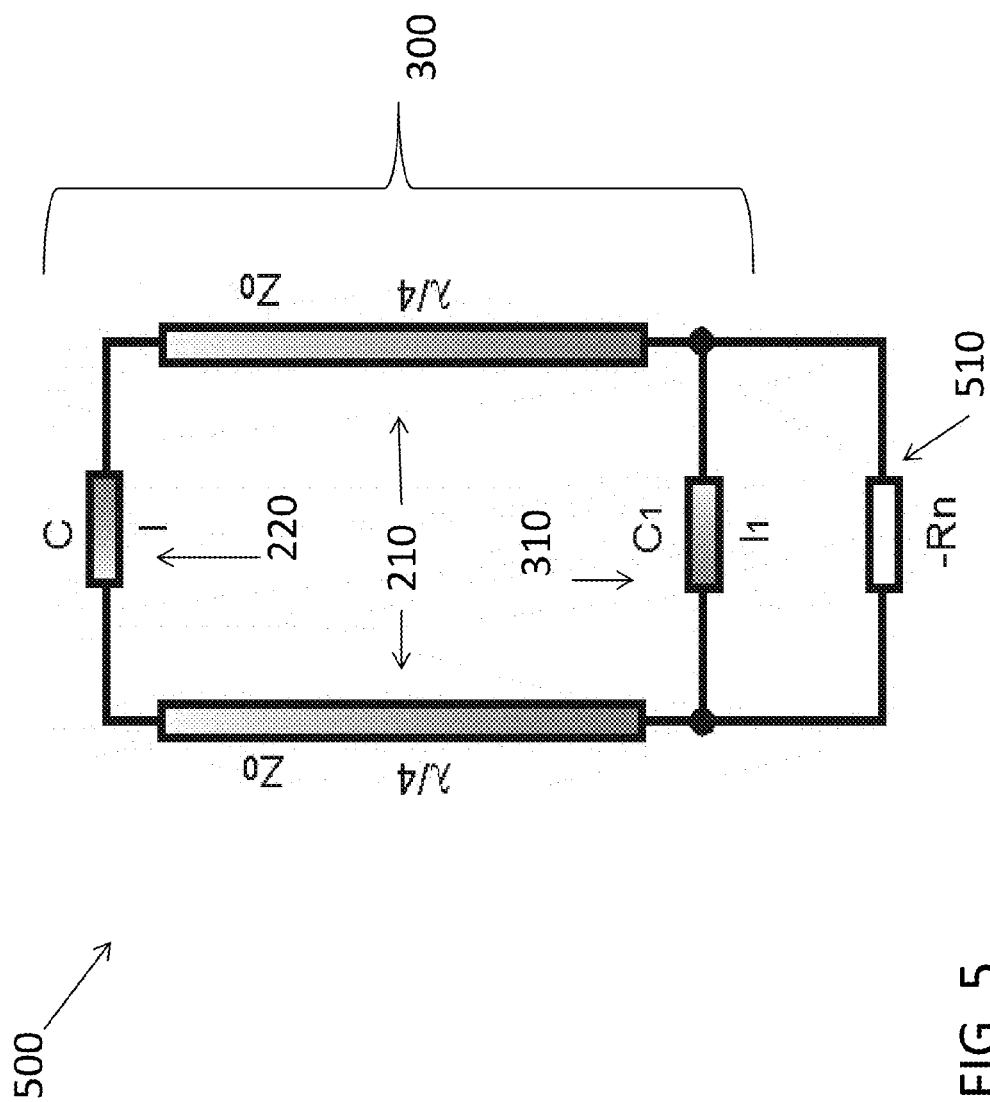


FIG. 5

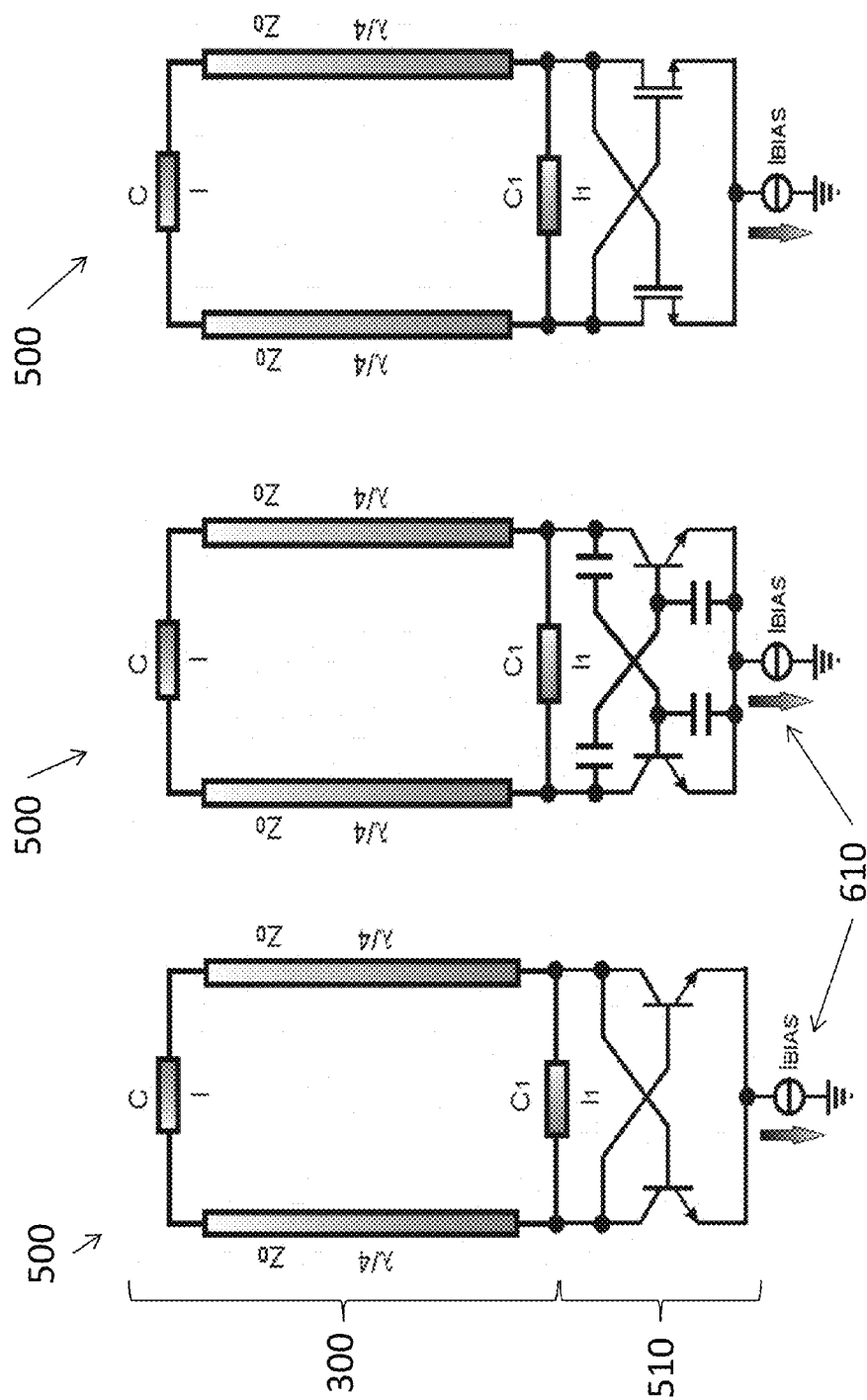


FIG. 6



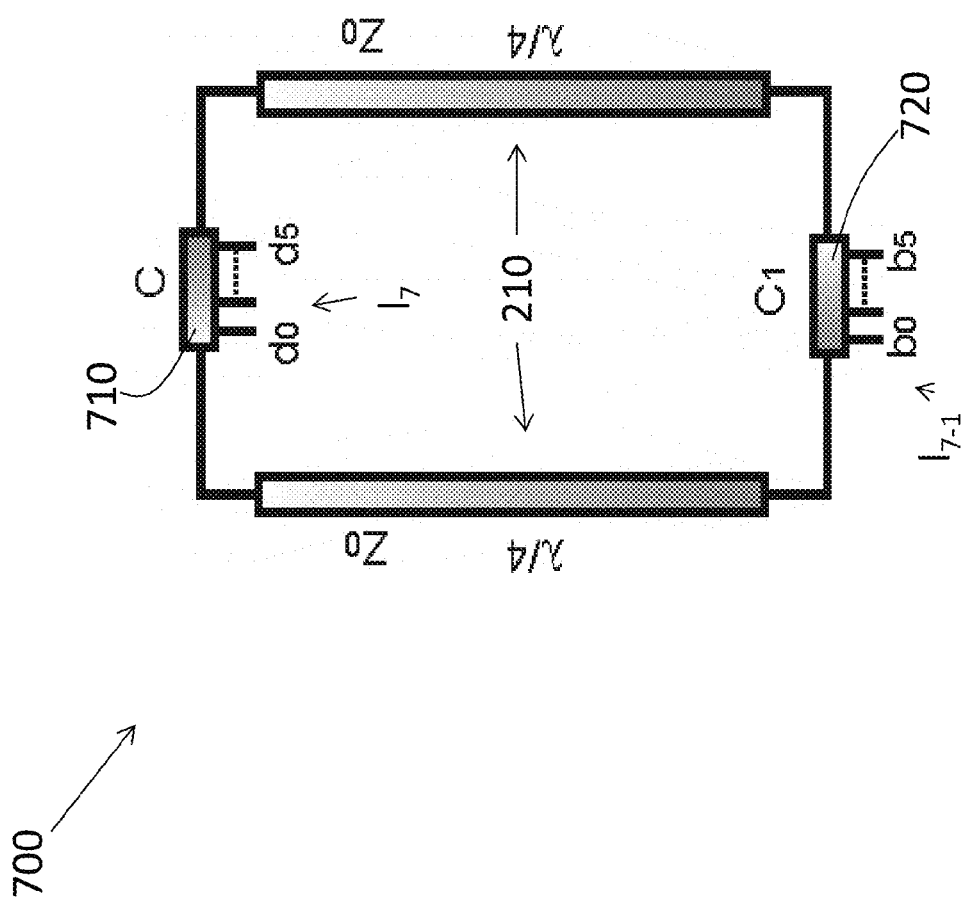
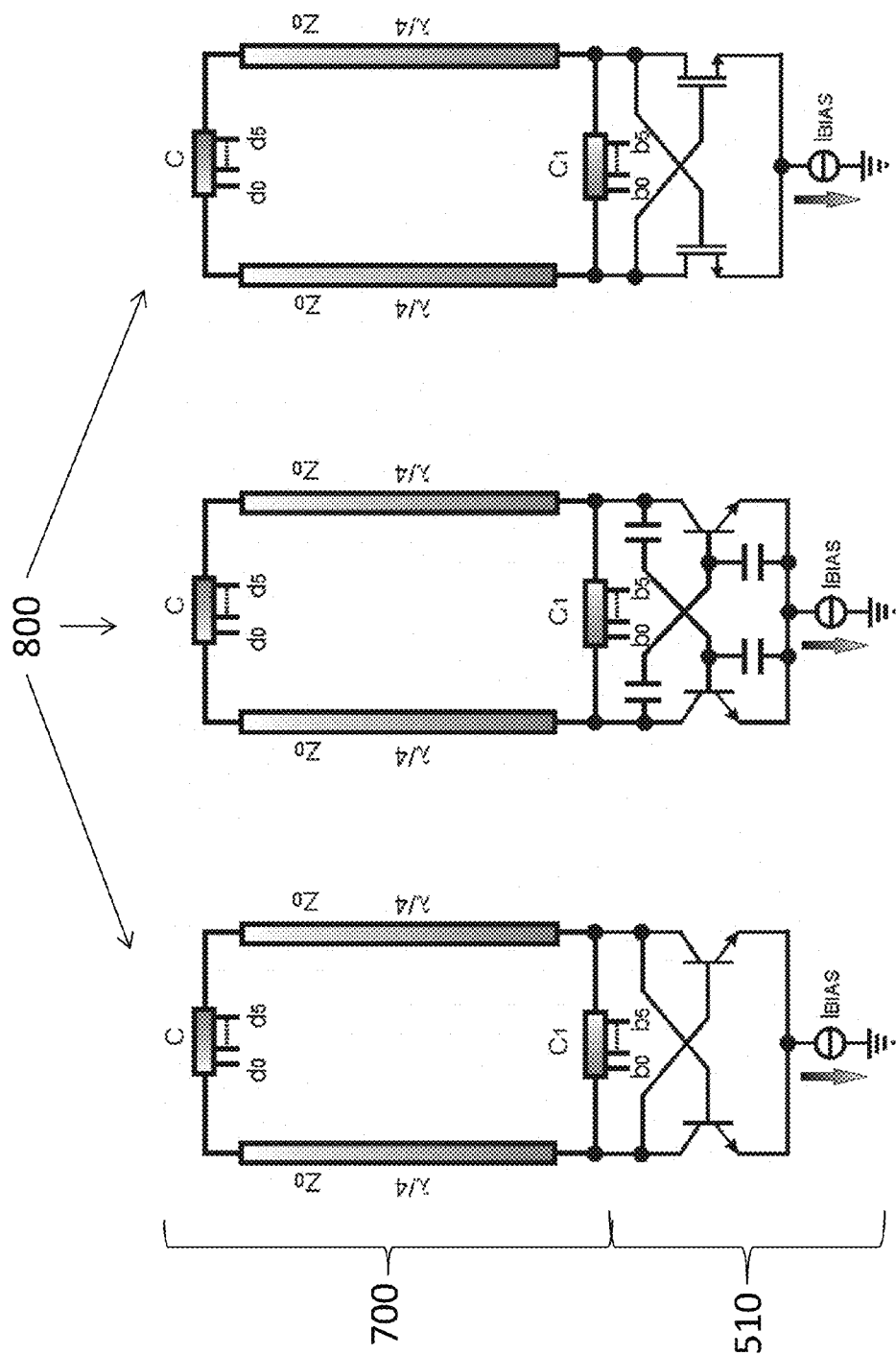


FIG. 7



8  
G.  
E.

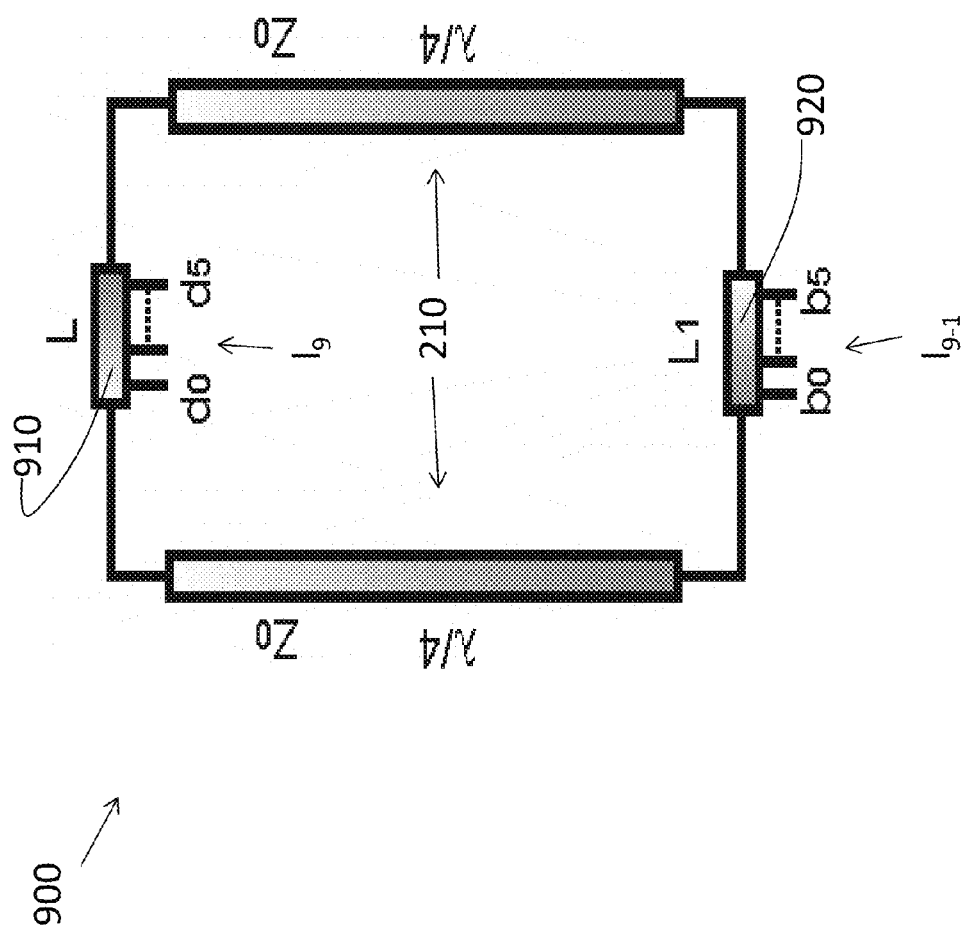


FIG. 9

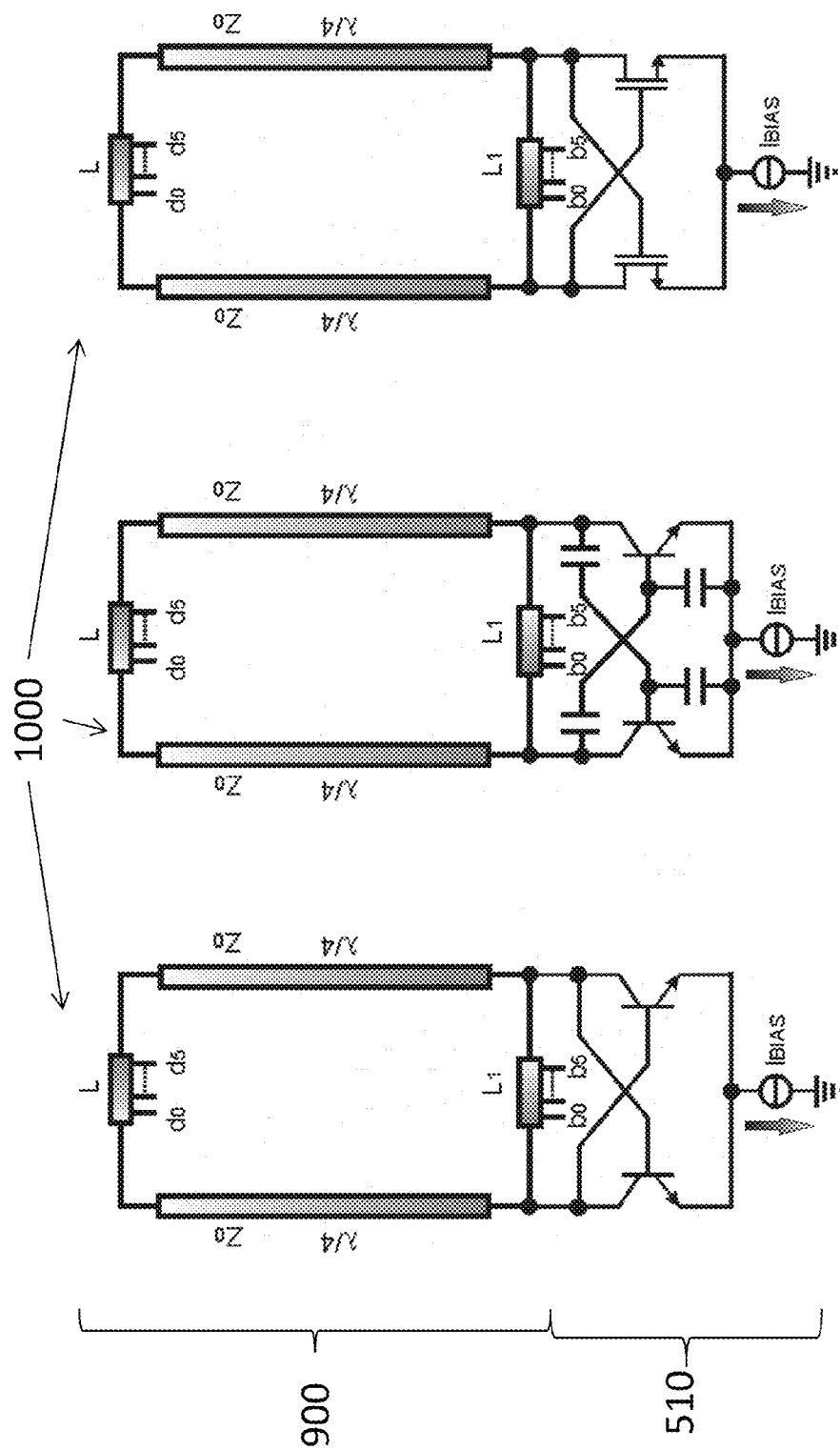


FIG. 10

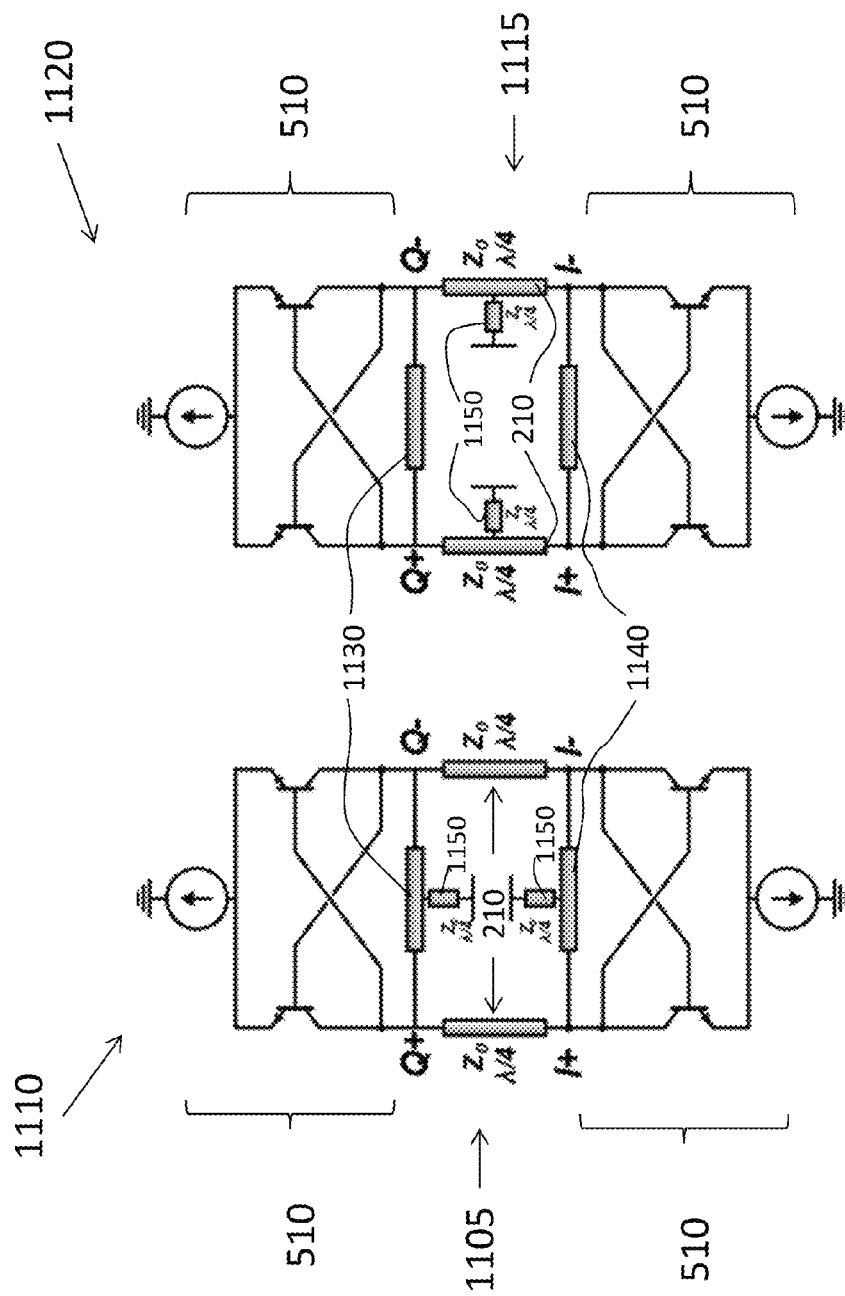


FIG. 11

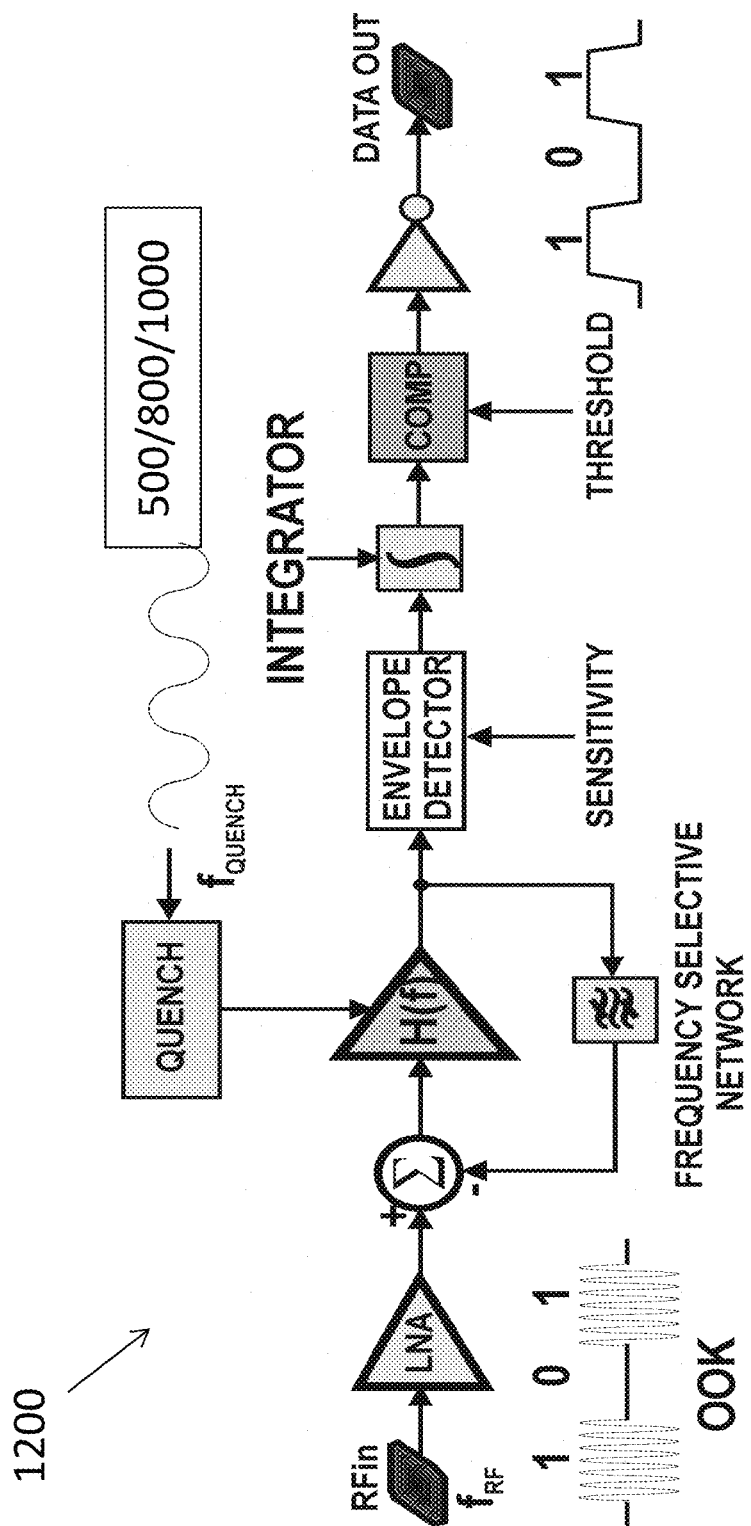


FIG. 12

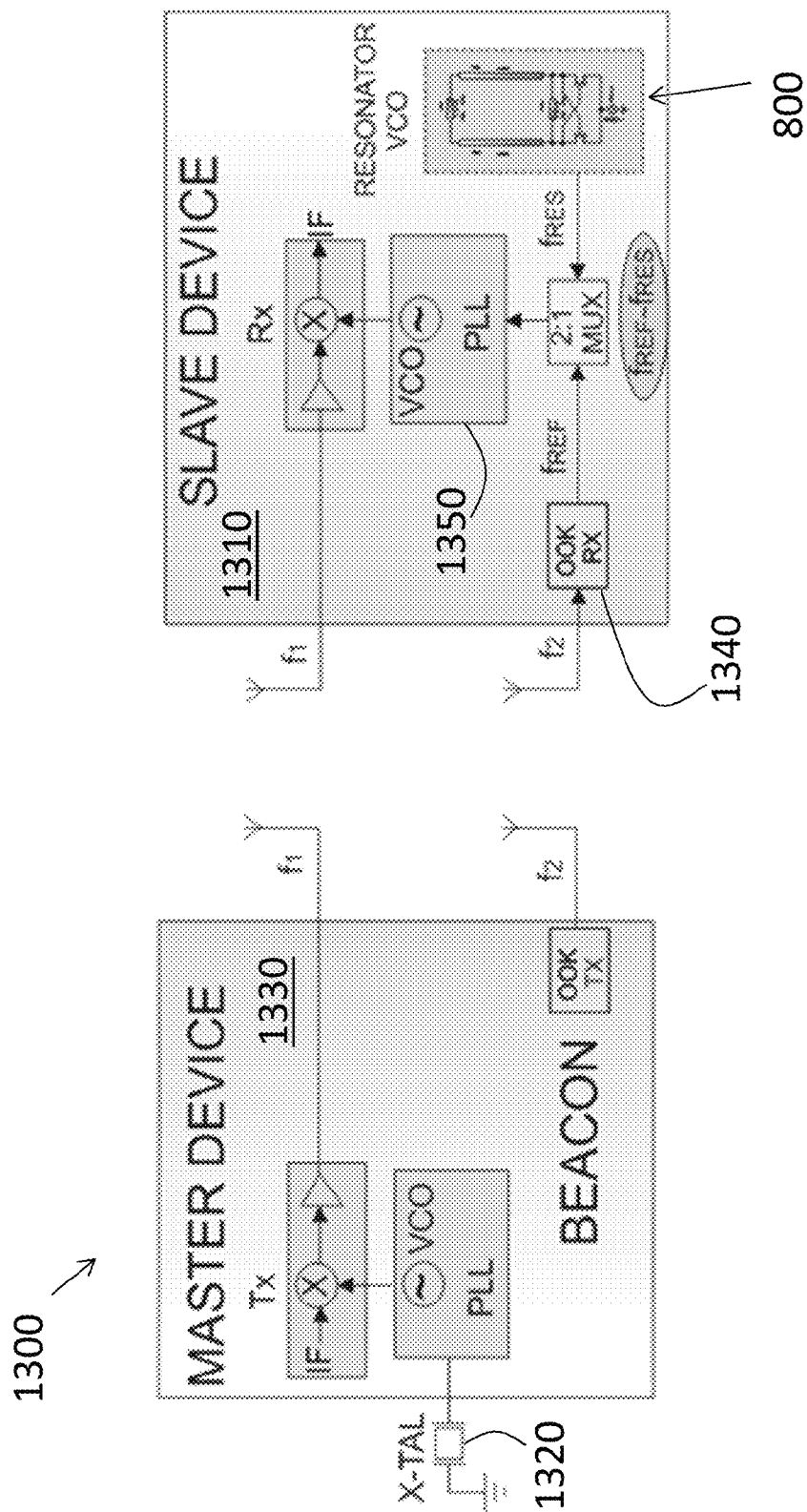


FIG. 13

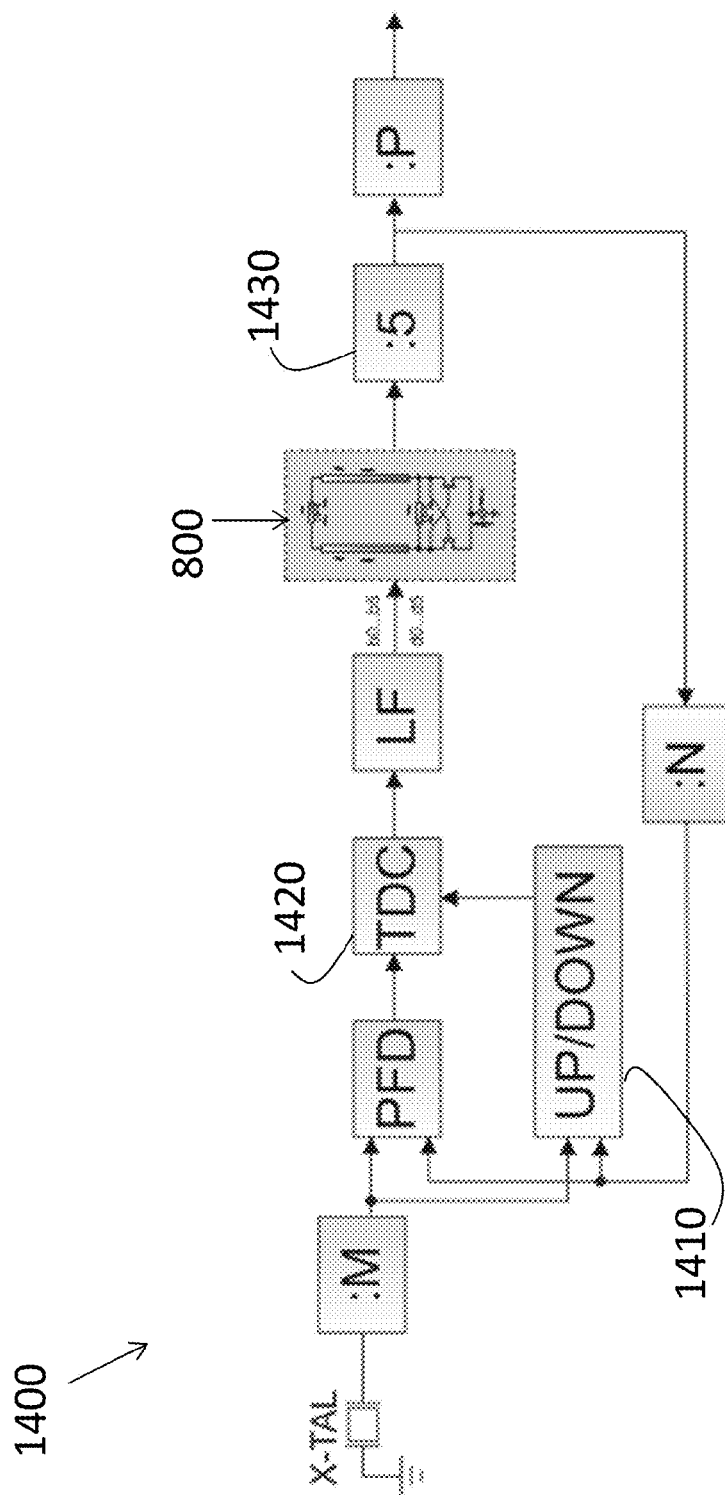
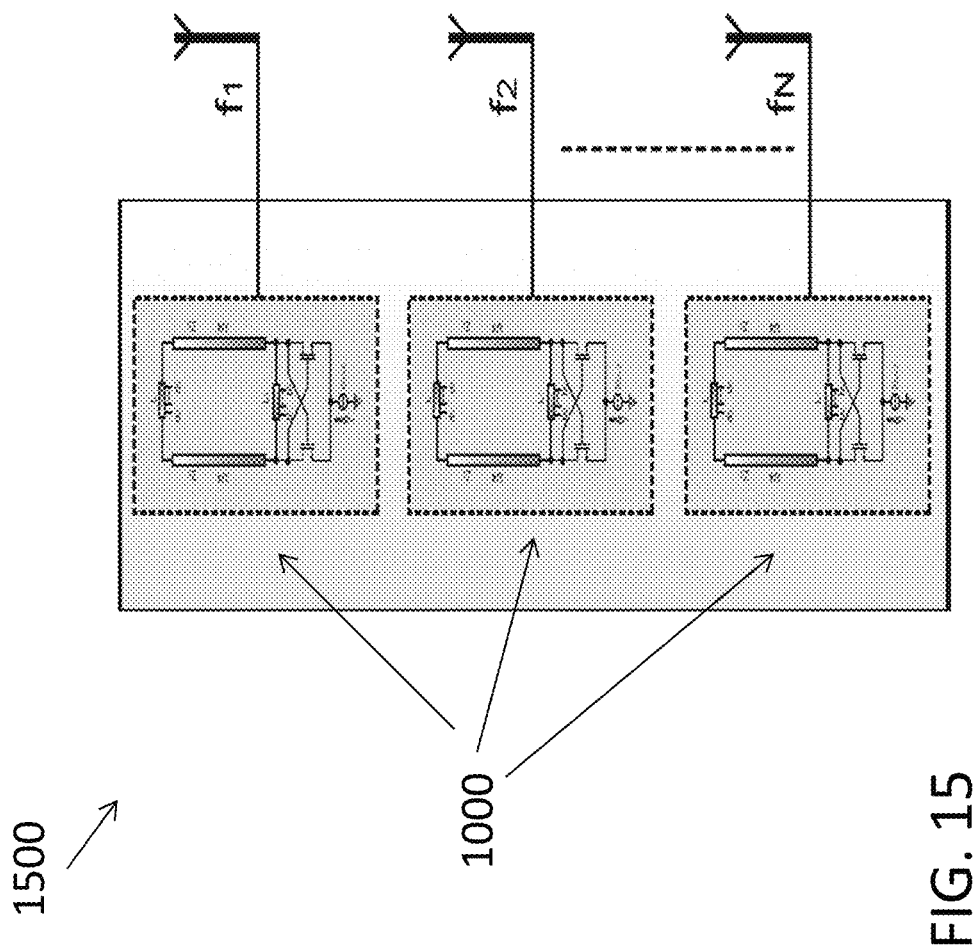


FIG. 14





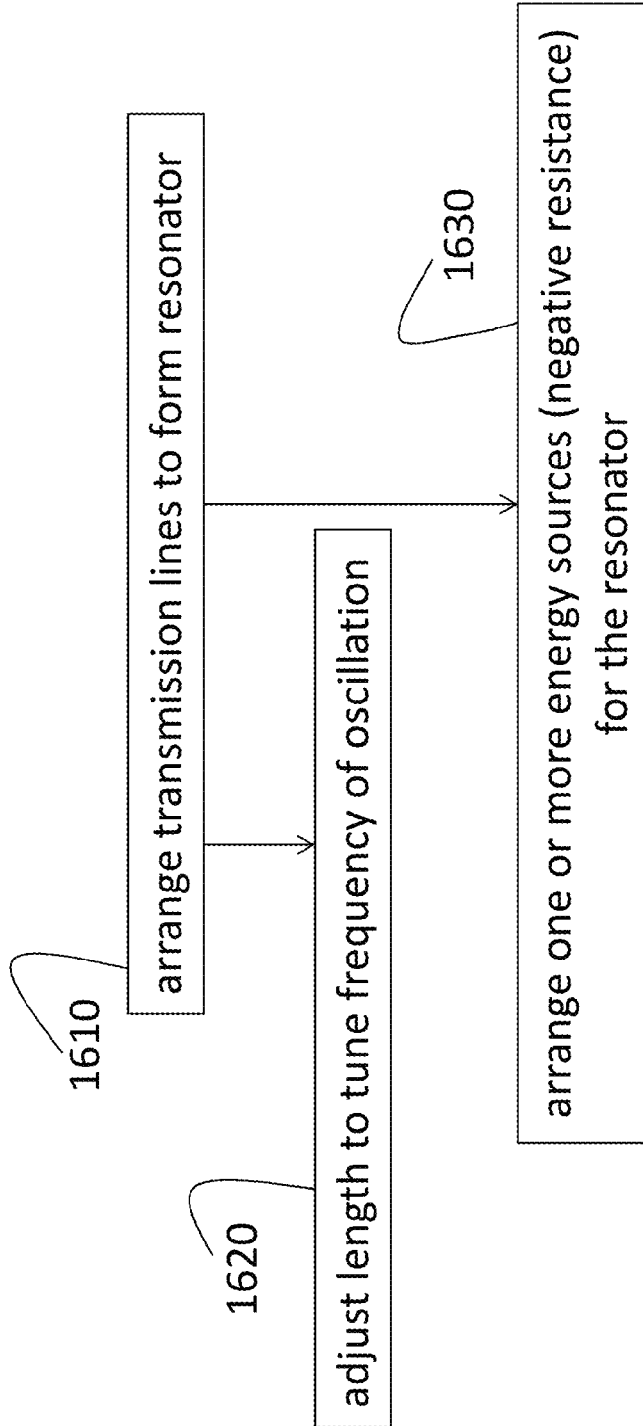


FIG. 16

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## SPEED OF LIGHT BASED OSCILLATOR FREQUENCY

### CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. application Ser. No. 14/036,205 filed Sep. 25, 2013, the disclosure of which is incorporated by reference herein in its entirety.

### BACKGROUND

The present invention relates to a transmission line resonator, and more specifically, to a speed of light referenced frequency oscillator.

The generation of signals having frequencies with wavelengths on the order of millimeters (mm-waves) is challenged by the lack of low phase-noise oscillators that work at the carrier frequency and have a large tuning range. On-chip complementary metal-oxide-semiconductor (CMOS) variable capacitances (varactors) have low quality factors (Qs) (e.g., less than 10). As a result, a voltage-controlled oscillator (VCO) based on integrated varactors may have a high phase noise and a limited tuning range. Currently available high-Q on-chip resonators are not only bulky but also have no means to tune their frequency characteristics. Alternative devices use a phase-locked loop (PLL) working at lower frequencies and frequency multipliers (e.g., doublers, triplers) to generate a mm-wave carrier. These multiplying devices need active devices and passive devices such as inductor and capacitors. Moreover, these multipliers have poor efficiency. As a result, there is a power penalty and area penalty to generate the higher frequencies. In addition, the generated signals at mm-waves need amplifiers and buffers to drive the up/down conversion mixers.

### SUMMARY

According to one embodiment of the present invention, an oscillator includes a resonator comprising a plurality of transmission lines, an oscillation frequency of the oscillator being independent of at least one dimension of the plurality of transmission lines; and a negative resistance circuit coupled to the resonator and configured to cancel internal loss resistance of the resonator.

According to another embodiment, a method of fabricating an oscillator includes arranging a plurality of transmission lines to form a resonator whose oscillation frequency is referenced to a speed of light and is independent of at least one dimension of the plurality of transmission lines; and coupling a negative resistance circuit to the resonator, the negative resistance circuit being configured to cancel internal loss resistance of the resonator.

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the invention are apparent from

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the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 illustrates a parallel plate transmission line according to an embodiment of the invention;

5 FIG. 2 shows a quarter lambda ( $\lambda/4$ ) transformer and a capacitor, both comprising the parallel plate transmission lines according to an embodiment of the invention;

FIG. 3 shows a transmission line resonator according to an embodiment of the invention;

10 FIG. 4 illustrates exemplary arrangements of the transmission lines of the resonator according to embodiments of the invention;

FIG. 5 depicts a fixed frequency oscillator according to an embodiment of the invention;

15 FIG. 6 illustrates exemplary oscillators according to different embodiments of the invention;

FIG. 7 depicts a variable frequency transmission line resonator including tunable capacitors according to an embodiment of the invention;

20 FIG. 8 illustrates exemplary oscillators including tunable capacitors according to embodiments of the invention;

FIG. 9 depicts a variable frequency transmission line resonator including tunable inductors according to an embodiment of the invention;

25 FIG. 10 illustrates exemplary oscillators including tunable inductors according to embodiments of the invention;

FIG. 11 shows quadrature oscillators according to embodiments of the invention;

30 FIG. 12 is a block diagram of an on-off keying receiver including the oscillator according to embodiments of the invention;

FIG. 13 is a block diagram of radios that include an oscillator according to an embodiment of the invention;

35 FIG. 14 is a block diagram of a mm-wave digital phase locked loop (PLL) that includes an oscillator according to an embodiment of the invention;

FIG. 15 is a block diagram of oscillators according to an embodiment of the invention that may be used in a terahertz (THz) source; and

40 FIG. 16 is a process flow of a method of fabricating an oscillator according to embodiments described herein.

### DETAILED DESCRIPTION

45 As noted above, oscillators that generate mm-wave frequency signals suffer from issues of phase noise and tuning range. Typically, a VCO includes a resonator in which a capacitor and inductor resonate to give the frequency of oscillation when provided with energy. Sources of inaccuracy can change the oscillation frequency. One source of inaccuracy is an inconsistency in the dimensions of the capacitor and inductor in the manufacturing. Embodiments of the resonator described herein provide a frequency of oscillation that is referenced to the speed of light and is independent of at least one dimension and up to two dimensions.

50 FIG. 1 illustrates a parallel plate transmission line 100 according to an embodiment of the invention. The transmission line 100 shown in FIG. 1 is a building block of the resonator 300 (see e.g., FIG. 3) according to embodiments of the invention. The transmission line 100 includes two metal plates 110a, 110b arranged in parallel with a dielectric material 120 separating them. The dimensions of the transmission line 100 are given by a length (l), width (w), and depth of the dielectric material 120 (d) which is the distance of separation between the two metal plates 110a, 110b. The resistance of the transmission line 100 ( $R_{Line}$ ) is given by:

$$R_{Line} = \frac{2}{w * \sigma_{cond} * \delta} \quad [EQ. 1]$$

where  $w$  is the width of the transmission line metal plates **110a** and **110b** as shown in FIG. 1,  $\sigma_{cond}$  is the conductance of the metal plates **110a**, **110b**, and  $\delta$  is the skin effect, which is given by:

$$\delta = \sqrt{\frac{2}{\omega * \mu * \sigma_{cond}}} \quad [EQ. 2]$$

where  $\omega$  is the frequency of the transmission line **100** in radians and  $\mu$  is the permeability. The inductance per unit length of the transmission line **100** ( $L_{Line}$ ) is given by:

$$L_{Line} = \mu_0 * \mu_r * \frac{d}{w} \left[ \frac{\text{Henry}}{\text{meter}} \right] \quad [EQ. 3]$$

Where  $d$  is the distance between the transmission line metal plates **110a** and **110b** as shown in FIG. 1,  $\mu_0$  (permeability in a vacuum) and  $\mu_r$  (relative permeability of the transmission line **100** with respect to  $\mu_0$ ) are the total permeability ( $\mu$ ). As EQ. 3 indicates, the inductance decreases as the width of the transmission line metal plates **110a** and **110b** increases. The capacitance per unit length of the transmission line **100** ( $C_{Line}$ ) is given by:

$$C_{Line} = \epsilon_0 * \epsilon_r * \frac{w}{d} \left[ \frac{\text{Farad}}{\text{meter}} \right] \quad [EQ. 4]$$

where  $\epsilon_0 * \epsilon_r$  is the total dielectric constant. As EQ. 4 indicates, the capacitance increases as the width of the transmission line metal plates **110a** and **110b** increases. That is, although FIGS. 2, 3, and 5-8 show capacitors, alternate embodiments of the invention include transmission lines **100** forming inductors (see e.g., FIGS. 9 and 10) based on the width of the transmission line metal plates **110a** and **110b** that make up the transmission lines **100**. The conductance per unit length of the transmission line **100** ( $G_{Line}$ ) is given by:

$$G_{Line} = \sigma_{cond} * \frac{w}{d} \left[ \frac{\text{Siemens}}{\text{meter}} \right] \quad [EQ. 5]$$

FIG. 2 shows a quarter lambda ( $\lambda/4$ ) transformer **200** and a capacitor **C 220**, both comprising the parallel plate transmission lines **100** according to an embodiment of the invention. The quarter lambda transformer **200** forms the inductor of the resonator **300** (see e.g., FIG. 3). As shown in FIG. 2, the quarter lambda transformer **200** comprises three transmission lines **100** as shown and discussed with reference to FIG. 1, the metal plate **110a** of each being visible in FIG. 2. The width ( $w$ ) and depth ( $d$ ) of each of the transmission lines **100** shown in FIG. 2 are assumed to be the same. The length ( $l$ ) of the waveguides **210** is a quarter of the wavelength corresponding to the transmission frequency, and the length of capacitor **C 220** is given by  $l_{cap}$  (capacitor **C 220** and the corresponding capacitance  $C$  are both references with  $C$ ). The input impedance (**230**)  $Z_{in}$  is given by:

$$Z_{in} = \frac{Z_0^2}{Z_C} = j\omega C * Z_0^2 = j\omega L \quad [EQ. 6]$$

where the impedance of the waveguides **210** is  $Z_0$ , the load or capacitor **220** impedance is  $Z_C$ ,  $C$  is the capacitance, and  $L$  is the inductance. As a result, using EQ. 6, the inductance  $L$  is given by:

$$L = Z_0^2 * C \quad [EQ. 7]$$

According to EQ. 4, which provides the capacitance per unit length, the capacitance  $C$  may also be written as:

$$C = \epsilon_0 * \epsilon_r * \frac{w}{d} * l \quad [EQ. 8]$$

In addition, the impedance of the waveguides **210** is given by:

$$Z_0 = \frac{d}{w} * \sqrt{\frac{\mu_0 * \mu_r}{\epsilon_0 * \epsilon_r}} \quad [EQ. 9]$$

By substituting the capacitor **C 220** capacitance ( $C$ ) from EQ. 8 and the waveguide **210** inductance ( $Z_0$ ) from EQ. 9 into EQ. 7, the inductance of the quarter lambda transformer **200** may be determined as:

$$L = \mu_0 * \mu_r * \frac{d * l}{w} \quad [EQ. 10]$$

FIG. 3 shows a transmission line resonator **300** according to an embodiment of the invention. The resonator **300** includes the quarter lambda transformer **200** shown in FIG. 2, which acts as the inductor of the resonator **300** with inductance indicated by EQ. 10. The resonator **300** also includes the capacitor  $C_1$  **310**, which acts as the capacitor of the resonator **300** with a capacitance given by:

$$C_1 = \epsilon_0 * \epsilon_r * \frac{w}{d} * l_1 \quad [EQ. 11]$$

where  $l_1$  is the length of the capacitor  $C_1$  **310**. With the inductance ( $L$ ) given by EQ. 10 and capacitance ( $C_1$ ) given by EQ. 11, the oscillation frequency ( $f_{osc}$ ) of the resonator **300** in Hertz (Hz) is:

$$f_{osc} = \frac{1}{2\pi\sqrt{LC_1}} = \frac{1}{2\pi\sqrt{l * l_1}} * \frac{c}{\sqrt{\epsilon_r * \mu_r}} \quad [EQ. 12]$$

where the speed of light ( $c$ ) is given by:

$$c = \frac{1}{\sqrt{\epsilon_0 * \mu_0}} \quad [EQ. 13]$$

As EQ. 12 illustrates, the frequency of oscillation of the resonator **300** is referenced to the speed of light ( $c$ ) and is independent of the width and depth of the transmission lines **100** that make up the resonator **300**. Instead, the oscillation

frequency depends on the lengths ( $l$  and  $l_1$ ) corresponding with the capacitors  $C_{220}$  and  $C_1 310$  and the material properties ( $\epsilon_r$  and  $\mu_r$ ) of the metal plates  $110a$  of the transmission lines  $100$ . The precision with which the oscillation frequency is attained depends on the precision of the mask involved in the processing of the integrated circuit. The precision of the oscillation frequency is represented by a variation ( $\Delta f_{osc}$ ) in the frequency of oscillation and is given by:

$$\frac{\Delta f_{osc}}{f_{osc}} = -\frac{1}{2} \left( \frac{\Delta l}{l} + \frac{\Delta l_1}{l_1} \right) \quad [\text{EQ. } 14]$$

FIG. 4 illustrates exemplary arrangements of the transmission lines  $100$  of the resonator  $300$  according to embodiments of the invention. The length of the waveguides  $210$  are always a quarter of the wavelength corresponding with the oscillation frequency. However, that length ( $\lambda/4$ ) may be implemented in a stepped fashion in some embodiments and as a straight line in other embodiments, as shown in FIG. 4. The overall length of the waveguides  $210$  according to any of the arrangements is a quarter of the wavelength corresponding with the oscillation frequency (the inductor of the resonator  $300$  is implemented as a quarter lambda transformer) and the oscillation frequency of the resonator  $300$  depends only on the lengths ( $l$  and  $l_1$ ) of the capacitors  $C_{220}$  and  $C_1 310$ , respectively.

FIG. 5 depicts a fixed frequency oscillator  $500$  according to an embodiment of the invention. The oscillator  $500$  includes the resonator  $300$  comprised of the transmission lines  $100$  and a negative resistance  $510$  ( $-R_N$ ). The negative resistance  $510$  ( $-R_N$ ) essentially creates a resonator  $300$  with no damping and can be thought of as adding energy to the system. If the oscillation loss of the resonator  $300$  were modeled as a resistance ( $R$ ), then the negative resistance  $510$  ( $-R_N$ ) cancels out the resistance ( $R$ ). FIG. 6 illustrates exemplary fixed frequency oscillators  $500$  according to different embodiments of the invention. FIG. 6 shows three different exemplary topologies of the oscillator  $500$  with three different implementations of the negative resistance  $510$  ( $-R_N$ ). Each of the exemplary topologies of the oscillator  $500$  also includes the application of a bias voltage resulting in the bias current  $610$ . The oscillators  $500$  may be used in CMOS or bipolar transistor applications.

FIG. 7 depicts a variable frequency transmission line  $100$  resonator  $700$  including tunable capacitors ( $C_{710}$  and  $C_1 720$ ) according to an embodiment of the invention. Like the resonator  $300$  shown in FIG. 3, the resonator  $700$  of FIG. 7 is implemented using transmission lines  $100$ . However, unlike the fixed-frequency resonator  $300$ , the resonator  $700$  has a tunable oscillation frequency as discussed below. The capacitors ( $C_{710}$  and  $C_1 720$ ) of the resonator  $700$  may be implemented as variable capacitors with variable lengths ( $l_7$  and  $l_{7-1}$ , respectively). Because the oscillation frequency depends on the lengths ( $l_7$  and  $l_{7-1}$ ) of the capacitors ( $C_{710}$  and  $C_1 720$ ) as shown in EQ. 12, the oscillation frequency varies as the lengths ( $l_7$  and  $l_{7-1}$ ) vary. As shown in FIG. 7, exemplary lengths ( $l_7$ ) for the transmission line  $100$  making up the capacitor  $C_{710}$  of the quarter lambda transformer (inductor of the resonator  $700$ ) may be within a range  $d_0$  through  $d_5$  with any number of incremental values in between. Exemplary lengths ( $l_{7-1}$ ) for the transmission line  $100$  making up the capacitor  $C_1 720$  of the resonator  $700$  may be within a range  $b_0$  through  $b_5$ . One or both of the lengths ( $l_7$  and  $l_{7-1}$ ) may be changed at one time to adjust the oscillator frequency. The capacitors ( $C_{710}$  and  $C_1 720$ ) may be tuned digitally. By tuning one or both of the capacitors ( $C_{710}$  and

$C_1 720$ ), the resonator  $700$  may be implemented as a tunable resonator with two independent tuning inputs. FIG. 8 illustrates exemplary oscillators  $800$  including tunable capacitors according to embodiments of the invention. The three different exemplary topologies of the oscillators  $800$  shown in FIG. 8 include tunable capacitors ( $C_{220}$  and  $C_1 310$ ) such that the oscillators  $800$  have tunable oscillation frequencies. FIG. 8 shows three different exemplary implementations of the negative resistance  $510$  ( $-R_N$ ). The three implementations of the negative resistance  $510$  ( $-R_N$ ) shown in FIG. 8 for the tunable oscillation frequency oscillators  $800$  are the same as those shown in FIG. 6 for the fixed oscillation frequency oscillators  $500$ .

FIG. 9 depicts a variable frequency transmission line  $100$  resonator  $900$  including tunable inductors ( $L_{910}$  and  $L_1 920$ ) according to an embodiment of the invention. The resonator  $900$  includes inductors  $L_{910}$  and  $L_1 920$  that have respective tunable lengths  $l_9$  and  $l_{9-1}$ . The relationship between inductance of the inductor  $L_{910}$  and capacitance is given by EQ. 7 above and depends on the impedance  $Z_0$  of the transmission lines  $100$  making up the waveguides  $210$ . The length ( $l_9$  and  $l_{9-1}$ ) of the inductors ( $L_{910}$  and  $L_1 920$ ) may be adjusted individually or collectively to adjust the oscillation frequency of the resonator  $900$ . While the same ranges ( $d_0$  through  $d_5$  and  $b_0$  through  $b_5$ ) of adjustment are shown for the lengths  $l_9$  and  $l_{9-1}$  of the inductors  $L_{910}$  and  $L_1 920$ , respectively, as are shown for the lengths  $l_7$  and  $l_{7-1}$  of the adjustable capacitors  $C_{710}$  and  $C_1 720$  shown in FIGS. 7 and 8, the ranges need not be the same. As with the resonator shown in FIG. 7, the resonator  $900$  of FIG. 9 is tunable with two independent inputs (i.e., inductor  $L_{910}$  and  $L_1 920$  lengths  $l_9$  and  $l_{9-1}$ ). FIG. 10 illustrates exemplary oscillators  $1000$  including tunable inductors ( $L_{910}$  and  $L_1 920$ ) according to embodiments of the invention. The three different exemplary topologies of the oscillators  $1000$  shown in FIG. 10 include tunable inductors ( $L_{910}$  and  $L_1 920$ ) such that the oscillators  $1000$  have tunable oscillation frequencies. FIG. 10 shows three different exemplary implementations of the negative resistance  $510$  ( $-R_N$ ). The three implementations of the negative resistance  $510$  ( $-R_N$ ) shown in FIG. 10 for the tunable oscillation frequency oscillators  $1000$  are the same as those shown in FIG. 6 (for the fixed oscillation frequency oscillators  $500$ ) and FIG. 8 (for the tunable oscillation frequency oscillators  $700$ ).

FIG. 11 shows quadrature oscillators  $1110$ ,  $1120$  according to embodiments of the invention. Each of the quadrature oscillators  $1110$ ,  $1120$  has a symmetric structure with an exemplary implementation of the negative resistance  $510$  ( $-R_N$ ) on each side of the resonator  $1105$ ,  $1115$ . As a result of the symmetrical arrangement, two output oscillation frequencies, with a 90 degree phase difference between them, are obtained from each of the quadrature oscillators  $1110$ ,  $1120$ . The resonators  $1105$ ,  $1115$  include the waveguides  $210$ . The other two transmission lines  $100$  ( $1130$ ,  $1140$ ) may be capacitors ( $220$ ,  $310$ ), as discussed with reference to FIG. 3, tunable capacitors ( $710$ ,  $720$ ), as discussed with reference to FIG. 7, or tunable inductors ( $910$ ,  $920$ ), as discussed with reference to FIG. 9. The resonators  $1105$ ,  $1115$  may be fabricated according to any of the embodiments discussed above. As such, the resonators  $1105$ ,  $1115$  have a quadrature oscillation frequency that is referenced to the speed of light and is independent of width ( $w$ ) and depth ( $d$ ) of the transmission lines  $100$  that comprise the resonators  $1105$ ,  $1115$  (see e.g., EQ. 12). Each of the resonators  $1105$ ,  $1115$  shows biasing, through quarter wavelength lines  $1150$ , of the transmission lines  $1130$ ,  $1140$  (in resonator  $1106$ ) or the waveguides  $210$  (in resonator  $1115$ ).

The various embodiments of the fixed frequency and variable frequency oscillators (**500, 800, 1000, 1110, 1120**) discussed above may be used in any application requiring an oscillator. For example, FIG. 12 is a block diagram of an on-off keying (OOK) receiver **1200** including the oscillator (**500, 800, 1000**) according to embodiments of the invention. In the OOK receiver **1200** according to one embodiment, the oscillator **500** may provide the quench signal. The oscillator **500** in this application may be generated with an on-chip reference based on a fixed resonator voltage controlled oscillator without an external crystal oscillator. The accuracy of the oscillator **500** frequency (quench frequency) may be precise within the mask accuracy and is acceptable as long as the frequency is greater than a multiple (e.g., 60 times) the receiver input frequency. The tunable oscillators (**800, 1000**) may also be used in this application. As another example, FIG. 13 is a block diagram of radios **1300** that include an oscillator **800** according to an embodiment of the invention. The oscillator **800** may be used as a reference for crystal-less radios **1300**. As FIG. 13 illustrates, the slave device **1310** has no crystal (like the crystal **1320** of the master device **1330**). The OOK receiver **1340** is always on. If a beacon from the master device **1330** is present, the phase locked loop (PLL) **1350** switches to the external reference ( $f_{REF}$ ) from the OOK receiver **1340**. Without the beacon from the master device **1330**, the PLL **1350** takes the reference from the on-chip oscillator **800**. The slave device **1310** locks to the master device **1330** immediately because the PLL **1350** acquires reference frequency ( $f_{REF}$ ) information from the beacon and the difference between  $f_{REF}$  and  $f_{RES}$  (the frequency from the oscillator **800**) is very small. Thus, the pull-in time for the PLL **1350** (to switch from  $f_{RES}$  to  $f_{REF}$  is very small). FIG. 14 is a block diagram of a millimeter wave (mm-wave) digital PLL **1400** that includes an oscillator **800** according to an embodiment of the invention. The up/down converter **1410** detects the sign of the time-to-digital converter (TDC) **1420**. The divider **1430** works at mm-waves and may be realized with resonant loads. As yet another example, FIG. 15 is a block diagram of oscillators **1000** according to an embodiment of the invention that may be used in a THz source **1500**.

FIG. 16 is a process flow of a method of fabricating an oscillator (**500, 800, 1000, 1110, 1120**) according to embodiments described herein. At block **1610**, arranging transmission lines **100** to form a resonator (**300, 700, 900, 1105, 1115**) may be according to the various embodiments described above. The transmission lines **100** used as waveguides **210** may be combined with a fixed-length capacitor (**C 220**) or variable-length capacitor (**C 710**) or variable-length inductor (**L 910**) and the resonator additionally includes a fixed-length capacitor (**C<sub>1</sub> 310**) or variable-length capacitor (**C<sub>1</sub> 720**) or variable-length inductor (**L<sub>1</sub> 920**). At block **1620**, adjusting the length to tune the frequency of oscillation includes adjusting the capacitor (**C 220, 710**) or inductor (**L 710**), adjusting the capacitor (**C<sub>1</sub> 310, 720**) or inductor (**L<sub>1</sub> 920**), or both as discussed with reference to FIGS. 7 and 9. At block **1630**, arranging one or more energy sources (negative resistance **510**) for the resonator (**300, 700, 900, 1105, 1115**) arranged according to blocks **1610** and, optionally, **1620** may include providing a single energy source to obtain an oscillator (**500, 800, 1000**) or two symmetric energy sources to obtain a quadratic oscillator (**1110, 1120**).

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “com-

prising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one more other features, integers, steps, operations, element components, and/or groups thereof.

The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

The flow diagram depicted herein is just one example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

While the preferred embodiment to the invention had been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

What is claimed is:

1. A method of fabricating an oscillator, the method comprising:
  - arranging a plurality of transmission lines to form a resonator whose oscillation frequency is a function of the speed of light and is independent of at least one dimension of the plurality of transmission lines; and
  - coupling a negative resistance circuit to the resonator, the negative resistance circuit being configured to cancel internal loss resistance of the resonator, wherein the arranging the plurality of transmission lines includes arranging four transmission lines and selecting a first transmission line and a second transmission line of the four transmission lines to have a respective first length and second length of one-fourth of a wavelength corresponding with the oscillation frequency.
2. The method according to claim 1, wherein the first transmission line and the second transmission line are separated by a third transmission line.
3. The method according to claim 1, wherein the arranging the four transmission lines includes selecting a third transmission line to have a third length that is different than the first length and the second length.
4. The method according to claim 1, wherein the arranging the four transmission lines includes selecting a third transmission line to have a third length that is a same length as the first length and the second length.
5. The method according to claim 1, further comprising adjusting a length of a third transmission line of the four transmission lines to tune the oscillation frequency.
6. The method according to claim 5, further comprising adjusting a length of a fourth transmission line of the four transmission lines to tune the oscillation frequency.
7. The method according to claim 1, further comprising coupling a second negative resistance circuit to the resonator.

8. The method according to claim 7, further comprising arranging the negative resistance circuit and the second negative resistance circuit symmetrically with respect to the resonator.

9. The method according to claim 8, wherein the oscillator is a quadrature oscillator providing two output signals having a same frequency that are 90 degrees out of phase with each other.

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